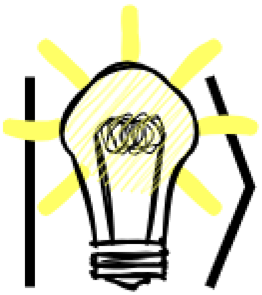
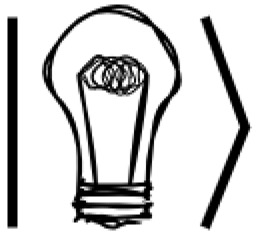




Investigating interference with phononic bright and dark states in a trapped ion

Robin Thomm

What makes stuff interfere?

Classical

Two electric fields: $\mathrm{E} = \left(1 + e^{i\,\delta\varphi}\right)E_0$

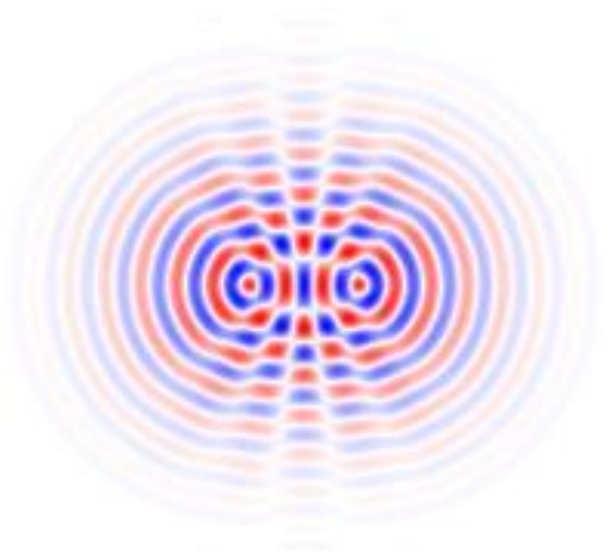
→ relative phase

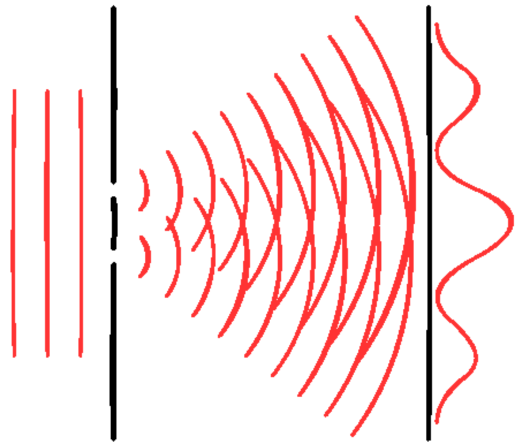
Quantum

$\langle n|\hat{E}|n\rangle = 0$ but coupling is present

Variances and/or higher moments?

→ Not so clear





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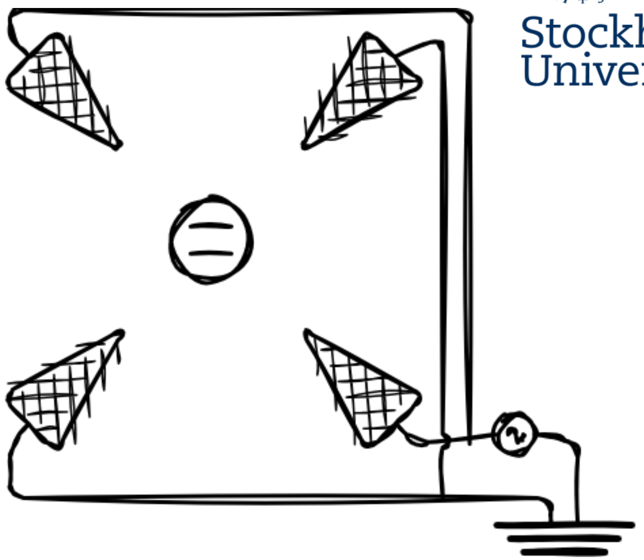

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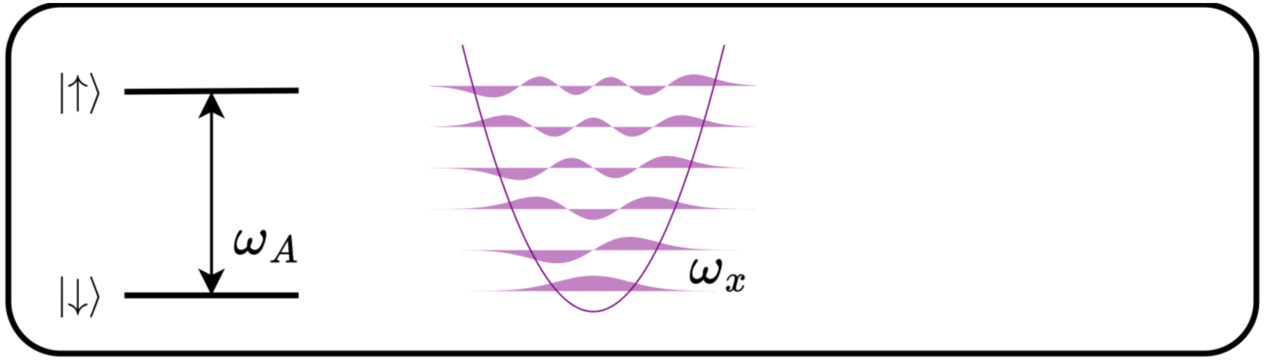

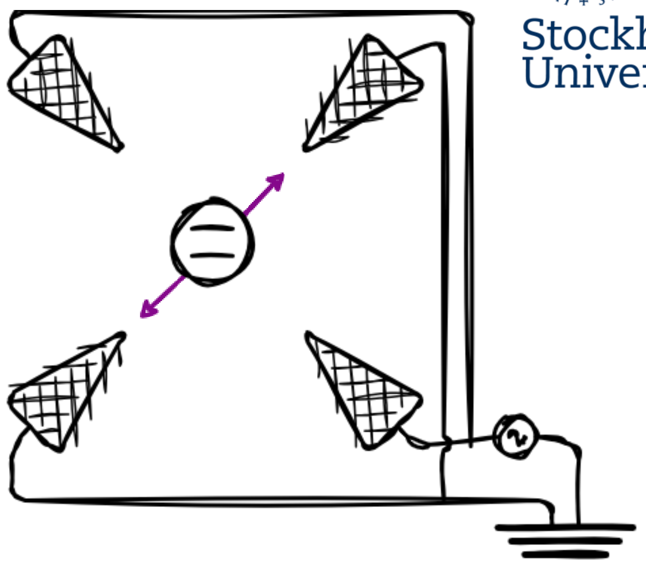

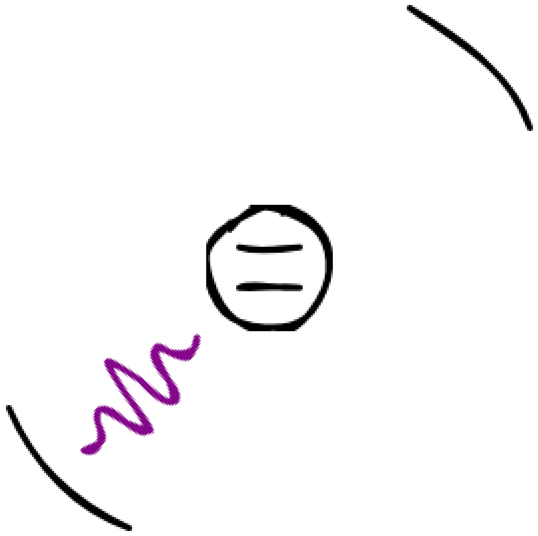

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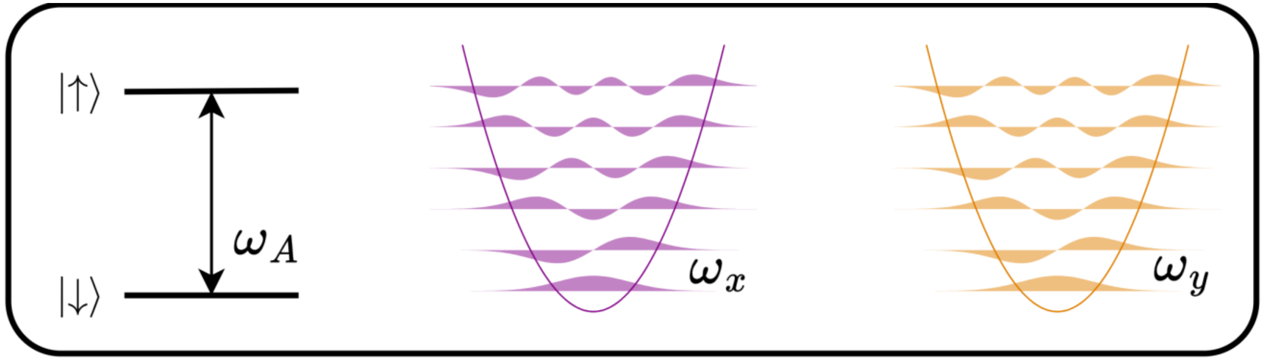
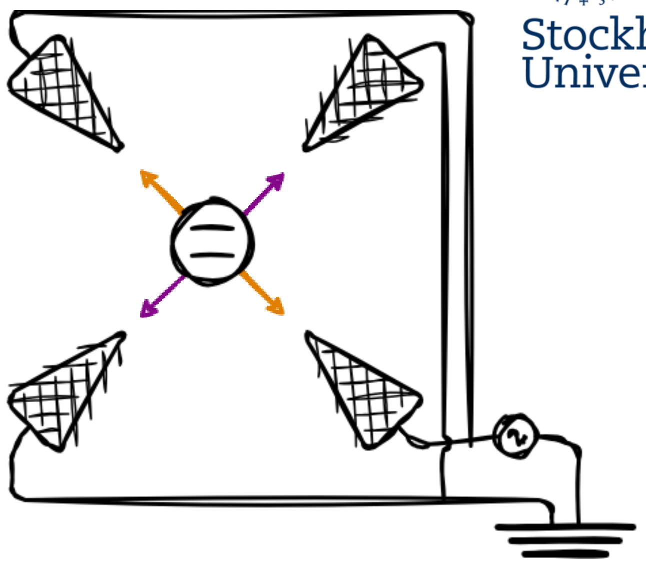
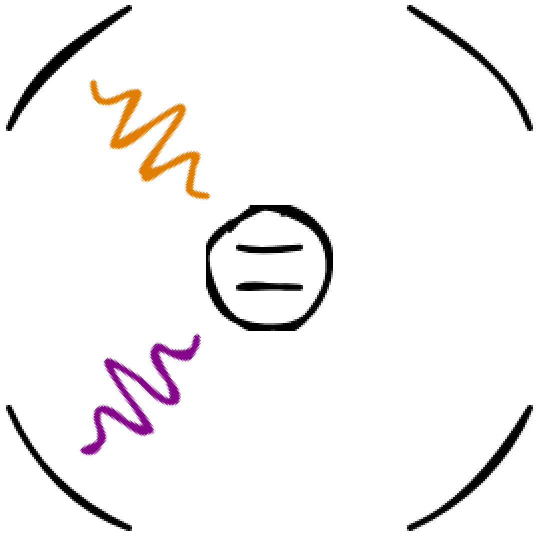
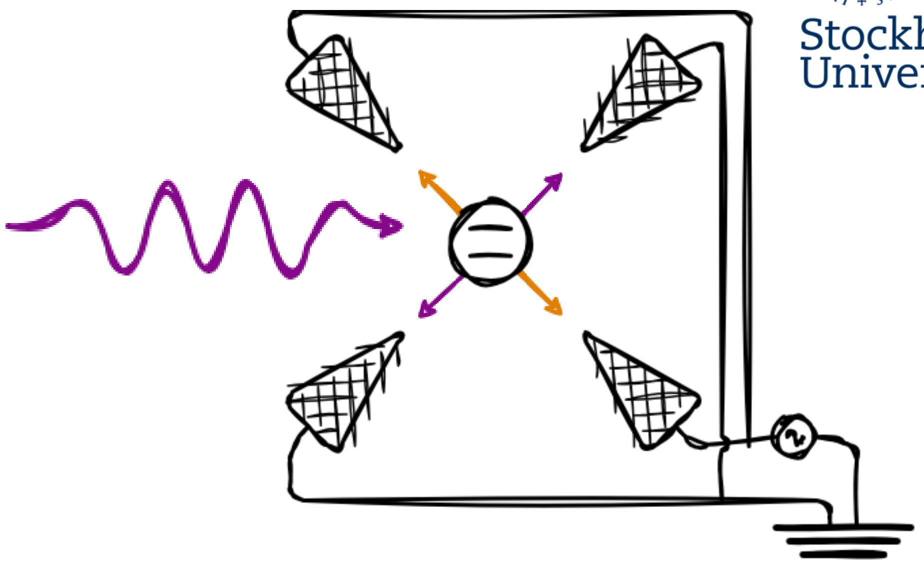
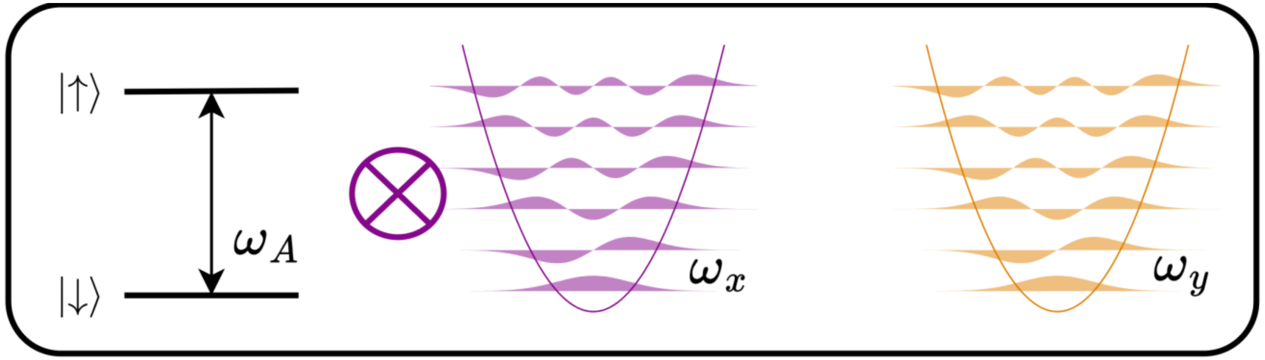


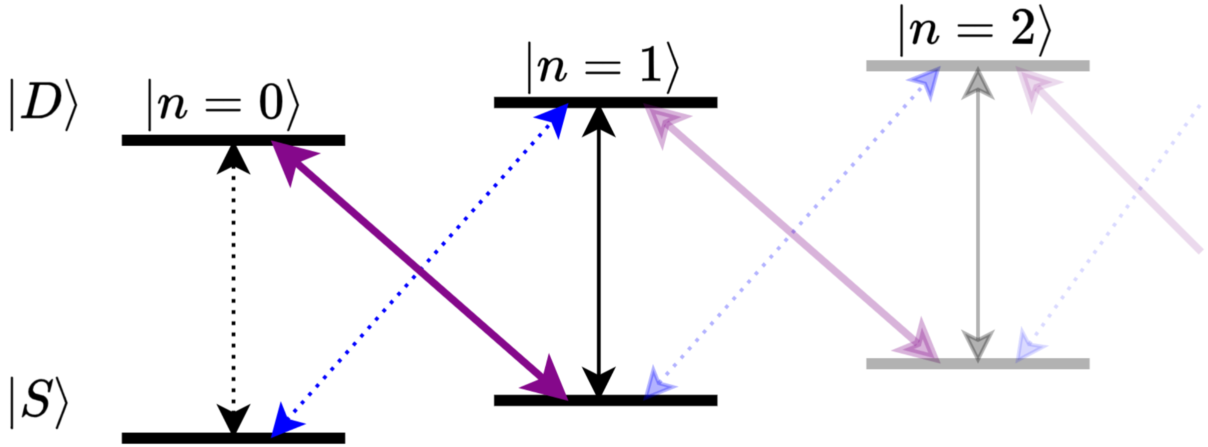


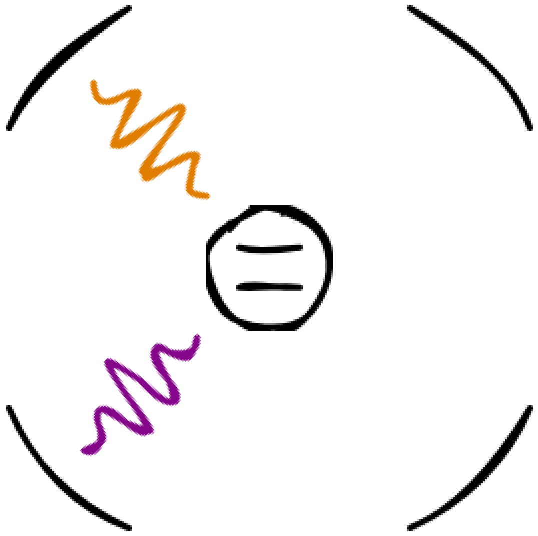


System

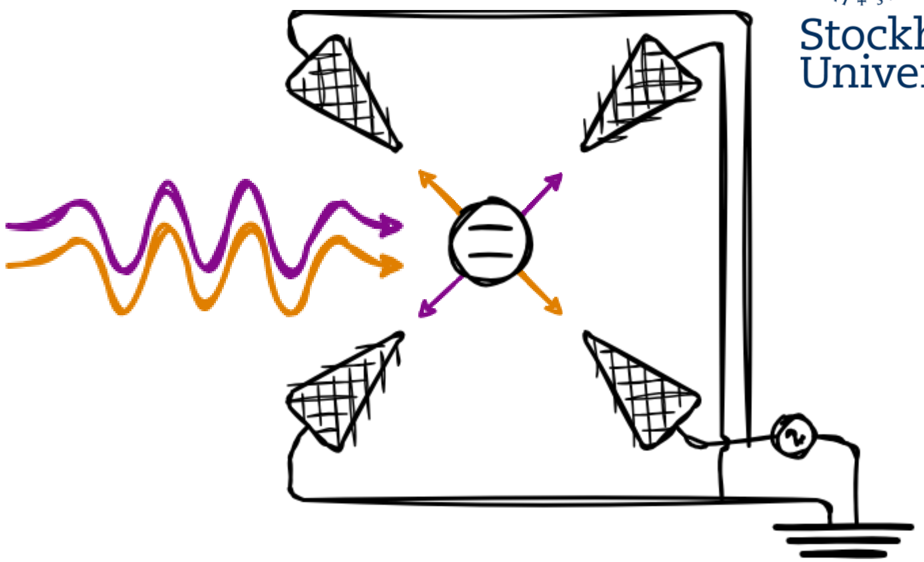


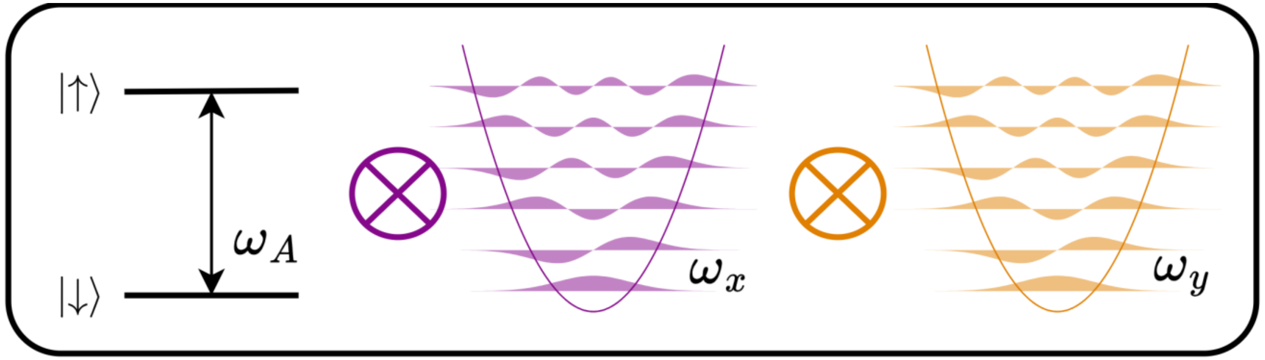

$|\uparrow\rangle$
$|\downarrow\rangle$
ω_A
ω_x
ω_y

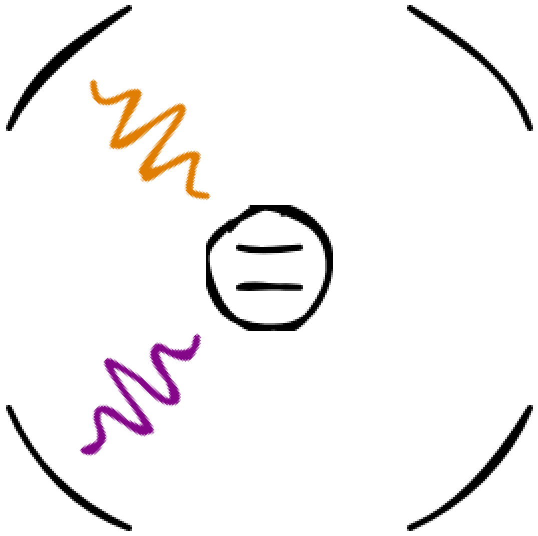

$|D\rangle$
$|S\rangle$
$|n=0\rangle$
$|n=1\rangle$
$|n=2\rangle$

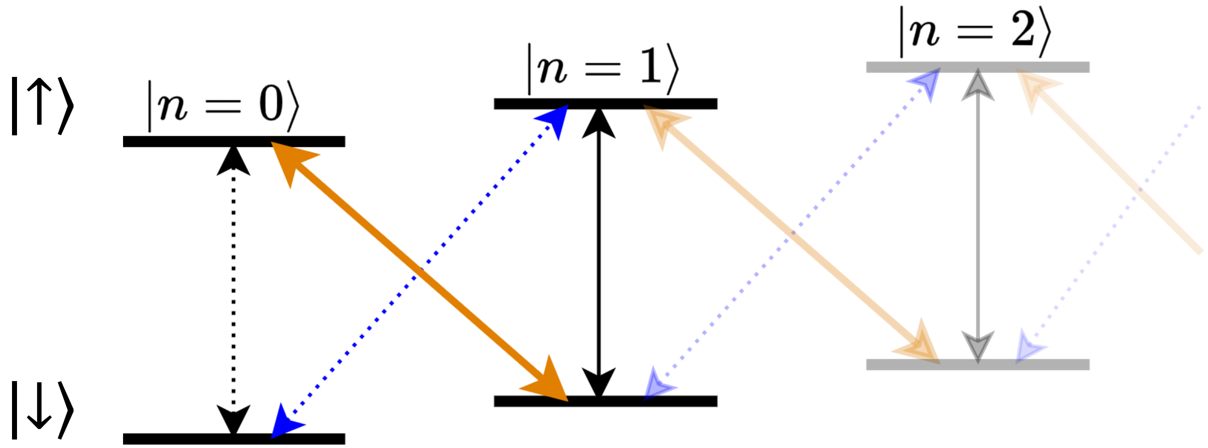


System

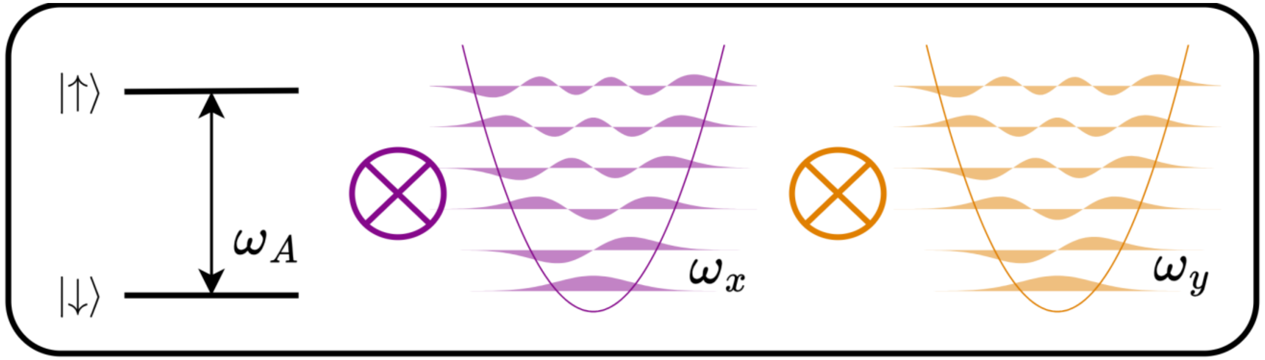


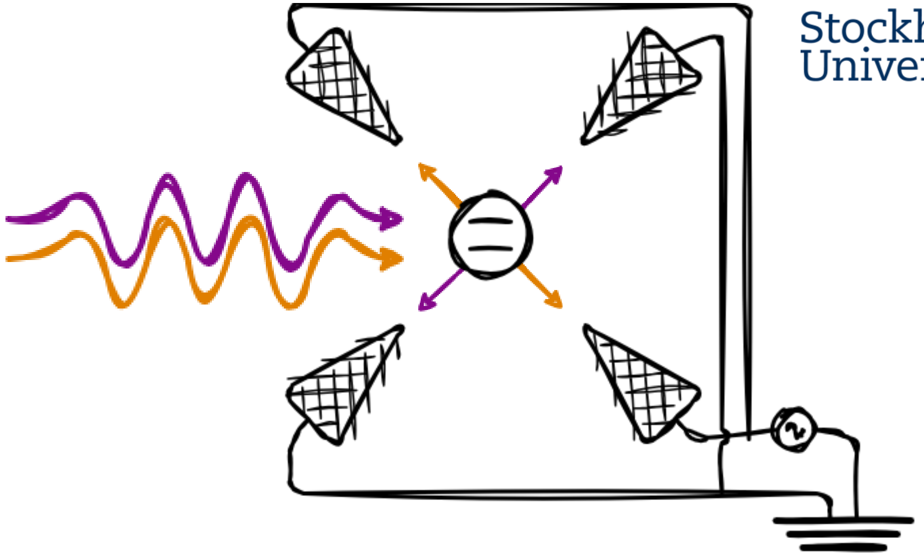

$|\uparrow\rangle$
$|\downarrow\rangle$
ω_A
ω_x
ω_y




$|\uparrow\rangle$
$|\downarrow\rangle$
$|n=0\rangle$
$|n=1\rangle$
$|n=2\rangle$

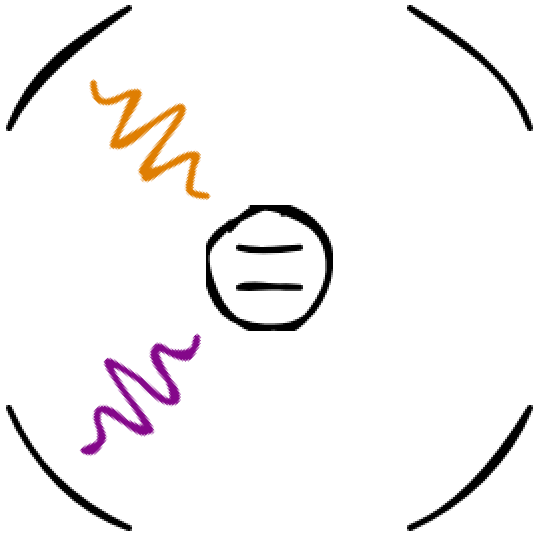
System



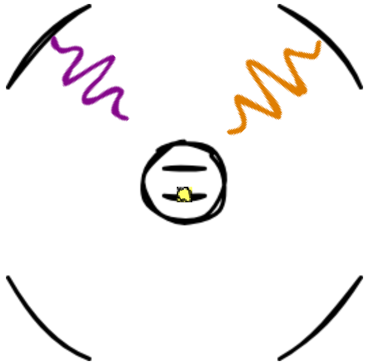


$\rightarrow$ $\boldsymbol{H = g\,(a_x + a_y)\sigma^{+} + g\,(a_x^{\dagger} + a_y^{\dagger})\sigma^{-}}$

→Jaynes-Cummings or RSB Hamiltonian



Theory



$$H = g\,(a_x + a_y)\sigma^+ + g\,(a_x^\dagger + a_y^\dagger)\sigma^-$$

Reference $\left|\Psi, 0\right\rangle$

$|1,0\rangle$

Time evolution

$\mathrm{H}|\downarrow\rangle|n,0\rangle = g\sqrt{n}|\uparrow\rangle|n-1,0\rangle$

→ Rabi oscillations

Coherent state

$|\alpha,0\rangle = \sum c_n|n,0\rangle$

Constr. Interference

$\left|\psi_+^1\right\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right)$

Time evolution

$\mathrm{H}|\downarrow\rangle|\psi_+^n\rangle = g\sqrt{2n}|\uparrow\rangle\left|\psi_+^{n-1}\right\rangle$

→ $\sqrt{2}$ faster

Coherent state

$|\psi_+^\alpha\rangle = |\alpha,\alpha\rangle = \sum c_n|\psi_+^n\rangle$

Destr. Interference

$\left|\psi_-^1\right\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle - |0,1\rangle\right)$

Time evolution

$\mathrm{H}|\downarrow\rangle|\psi_-^n\rangle = 0$

→ No population transfer

Coherent state

$|\psi_-^\alpha\rangle = |\alpha,-\alpha\rangle = \sum c_n|\psi_-^n\rangle$

Villas-Boas, C. J. *et al.* Bright and dark states of light: The quantum origin of classical interference *arxiv 2021*

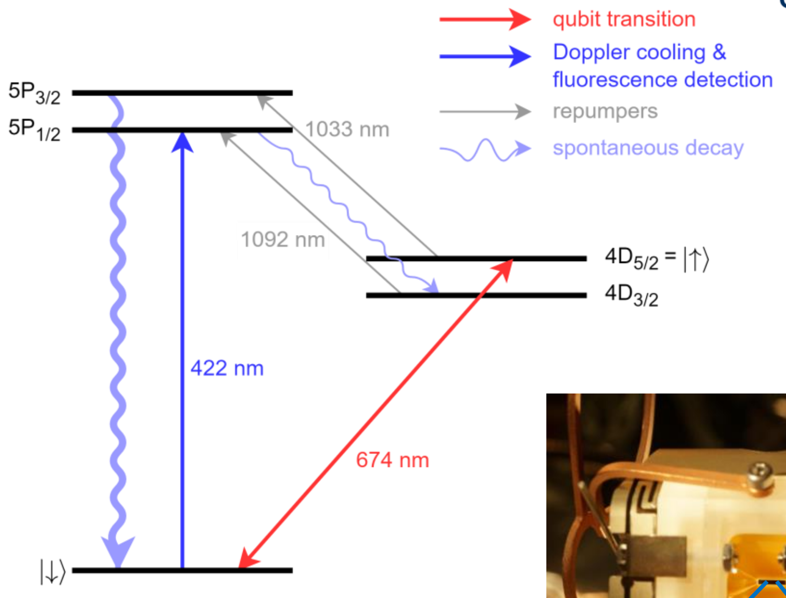
Experimental setup

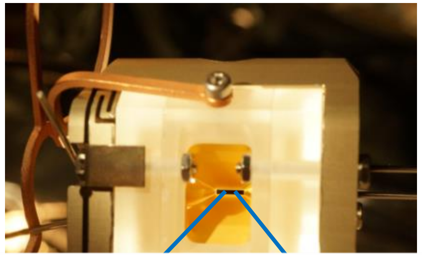
The ion
- A single $^{88}Sr^+$ ion
- Qubit: $|S\rangle$ and $|D\rangle$, initially in $|S\rangle$

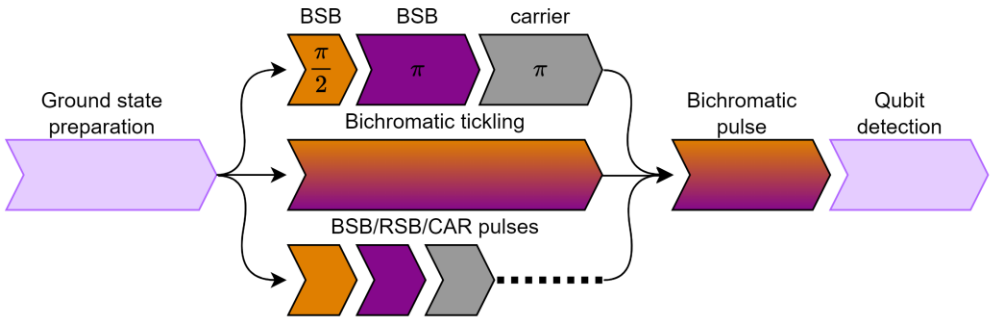
The trap
- Linear Paul trap
- Use both radial modes

State preparation
- Ground state preparation ($\bar{n} < 0.1$)
- Tickling or BSB & RSB pulses

Coupling
- Driving both RSBs simultaneously
- Bichromatic laser with 45° overlapp with both modes

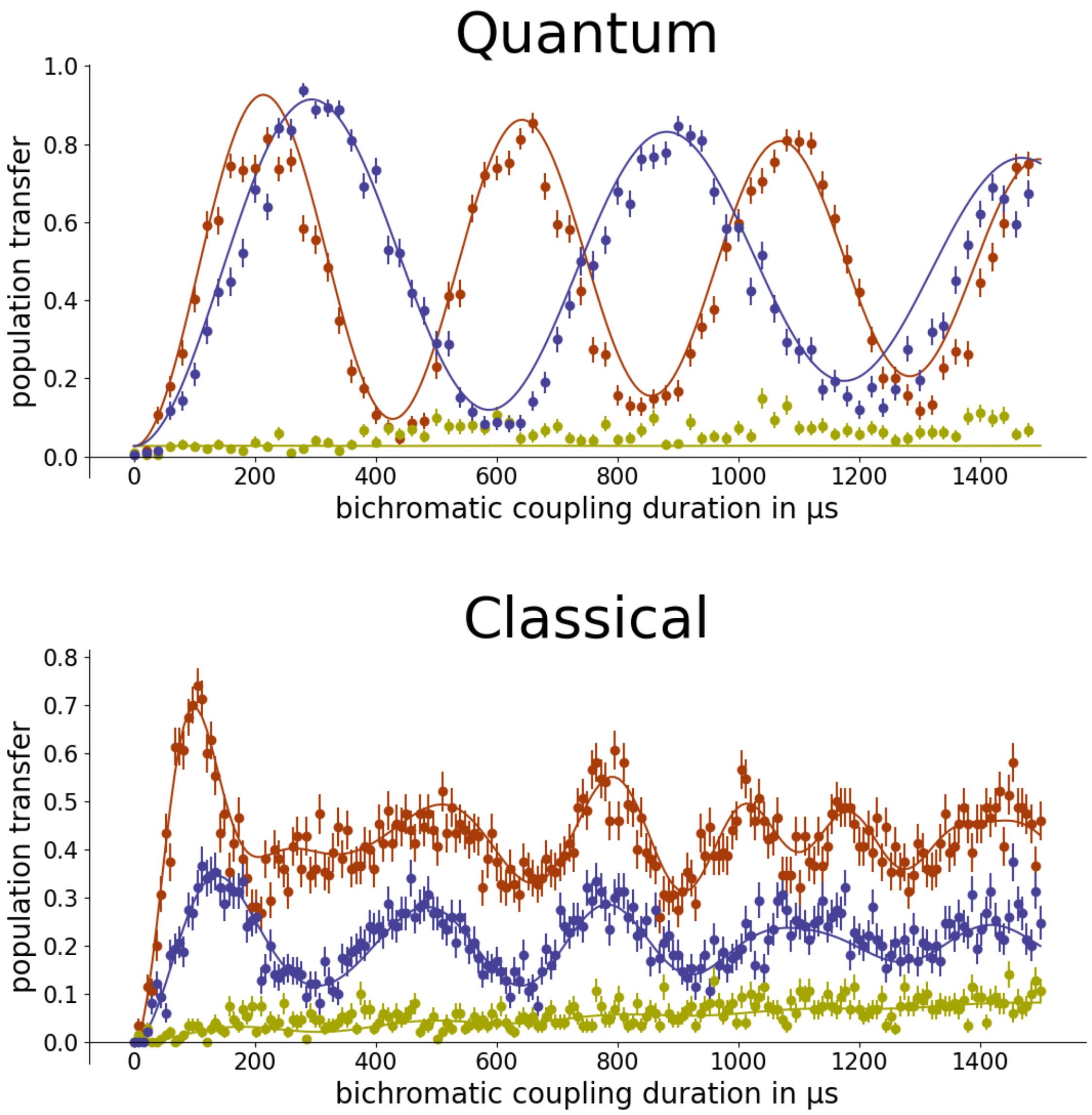






Results

Quantum	Classical
$\frac{1}{\sqrt{2}}(\vert 1,0\rangle + \vert 0,1\rangle)$	$\vert\alpha,\alpha\rangle$
$\frac{1}{\sqrt{2}}(\vert 1,0\rangle - \vert 0,1\rangle)$	$\vert\alpha,-\alpha\rangle$
$\vert 1,0\rangle$	$\vert\alpha,0\rangle$



Product state

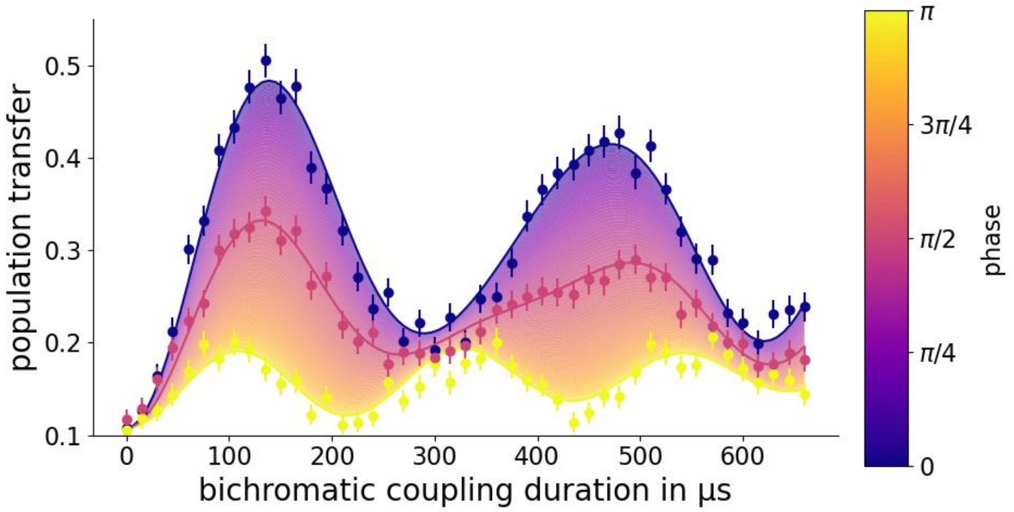
$$|\Upsilon_\varphi\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle + e^{i\varphi}|1\rangle)$$

$$|\Upsilon_\pi\rangle = \frac{1}{2}\left(|\psi_-^0\rangle - \sqrt{2}|\psi_-^1\rangle + \frac{1}{\sqrt{2}}\left[|\psi_-^2\rangle - |\psi_+^2\rangle\right]\right)$$

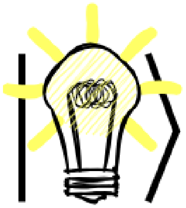
$$|\Upsilon_0\rangle = \frac{1}{2}\left(|\psi_-^0\rangle + \sqrt{2}|\psi_+^1\rangle - \frac{1}{\sqrt{2}}\left[|\psi_-^2\rangle - |\psi_+^2\rangle\right]\right)$$

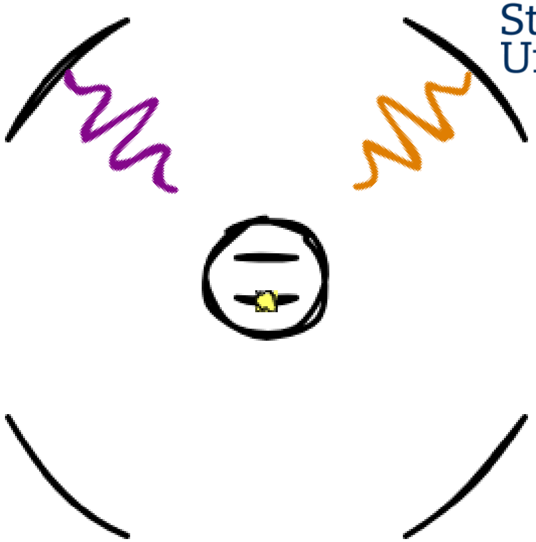
$|\Upsilon_\pi\rangle$: $\langle E\rangle = 0$ and $\langle \Delta E\rangle^2 = 2$

same as for the dark coherent state

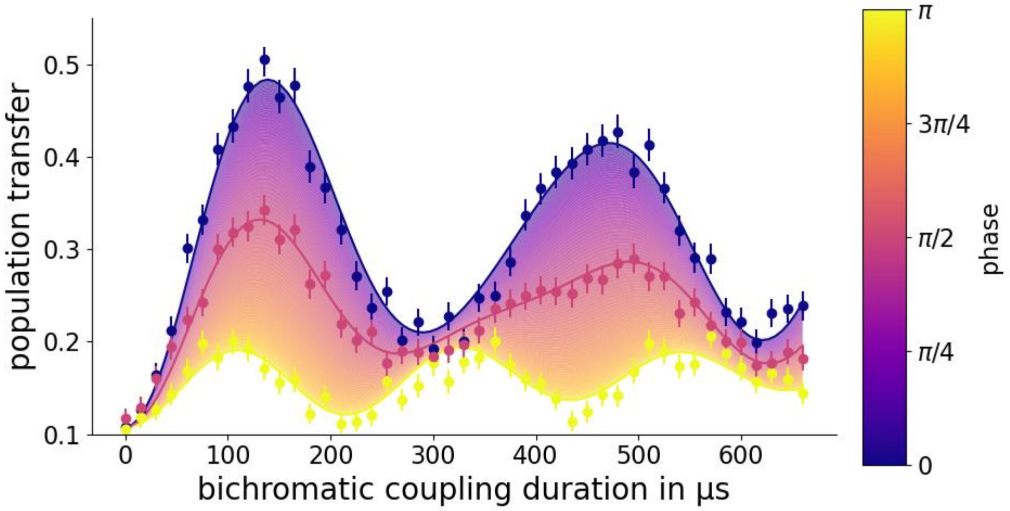


Conclusions





- Observed constructive and destructive interference
- Two mode basis:
  - Intuitive description of the interference
- What makes stuff interfere?
  - Not just expectation values and variances



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Brisk Rydberg Ions for Scalable Quantum Processors

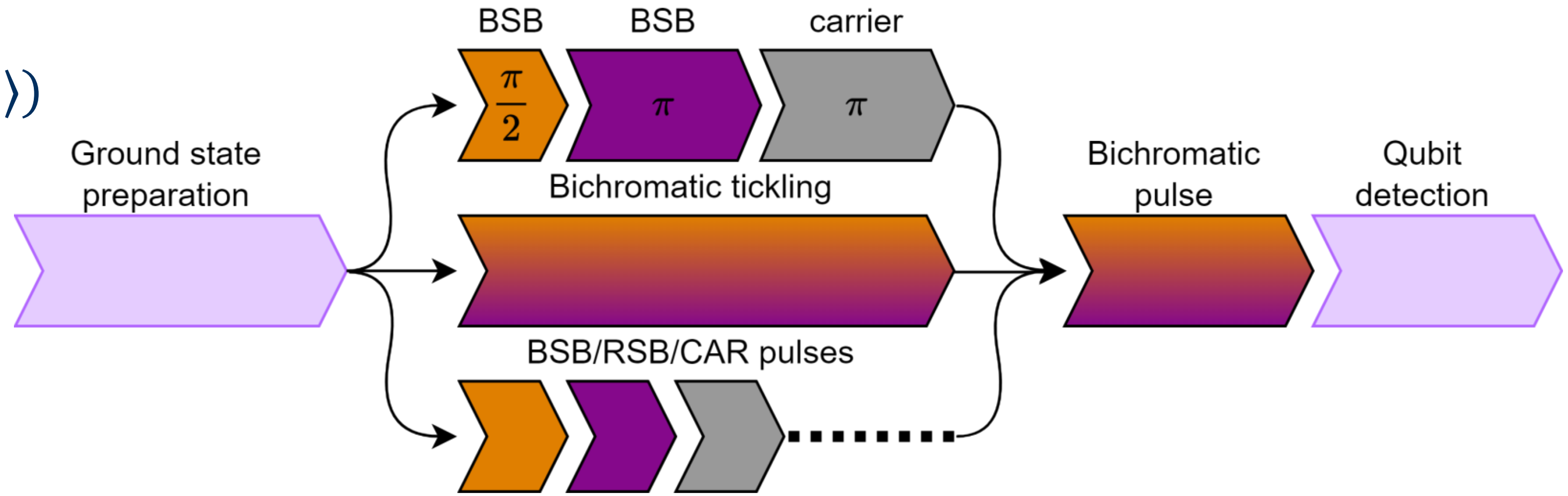
Knut och Alice Wallenbergs Stiftelse

Pulse sequence

$$\left|\psi_{\pm}^{1}\right\rangle = \frac{1}{\sqrt{2}}\left(|1,0\rangle \pm |0,1\rangle\right)$$

$$\left|\psi_{\pm}^{\alpha}\right\rangle = |\alpha, \pm\alpha\rangle$$

Product state $|\Upsilon_{\varphi}\rangle$



Creation of the weird state

$$|\downarrow,0,0\rangle$$

$\downarrow$ $\pi/3$ pulse on BSB_1

$$\frac{3}{4}|\downarrow,0,0\rangle+\frac{1}{4}|\uparrow,1,0\rangle$$

$\downarrow$ $\pi/2.55$ pulse on BSB_2 with phase φ_2

$$\frac{1}{2}|\downarrow,0,0\rangle+\frac{1}{4}|\uparrow,1,0\rangle+e^{i\varphi_2}\frac{1}{4}|\uparrow,0,1\rangle$$

$\downarrow$ π pulse on CAR_A

$$\frac{1}{2}|\uparrow,0,0\rangle+\frac{1}{4}|\downarrow,1,0\rangle+e^{i\varphi_2}\frac{1}{4}|\downarrow,0,1\rangle$$

$\downarrow$ π pulse on CAR_B

$$\frac{1}{2}|\uparrow,0,0\rangle+\frac{1}{4}|\uparrow',1,0\rangle+e^{i\varphi_2}\frac{1}{4}|\uparrow',0,1\rangle$$

Here we perform a round of postselection to discard any results in which imperfect transfer efficiencies cause the ground state $|\downarrow\rangle$ to remain populated. The preparation continues as:

$$\frac{1}{2}|\uparrow,0,0\rangle+\frac{1}{4}|\uparrow',1,0\rangle+e^{i\varphi_2}\frac{1}{4}|\uparrow',0,1\rangle$$

$\downarrow$ π pulse on CAR_A

$$\frac{1}{2}|\downarrow,0,0\rangle+\frac{1}{4}|\uparrow',1,0\rangle+e^{i\varphi_2}\frac{1}{4}|\uparrow',0,1\rangle$$

$\downarrow$ $\pi/2$ pulse on BSB_1 with phase φ_1

$$\frac{1}{4}\left\{|\downarrow,0,0\rangle+e^{i\varphi_1}|\uparrow,1,0\rangle+|\uparrow',1,0\rangle+e^{i\varphi_2}|\uparrow',0,1\rangle\right\}$$

$\downarrow$ π pulse on RSB_1

$$\frac{1}{4}\left\{|\downarrow,0,0\rangle+e^{i\varphi_1}|\downarrow,1,1\rangle+|\uparrow',1,0\rangle+e^{i\varphi_2}|\uparrow',0,1\rangle\right\}$$

$\downarrow$ $\pi/2$ pulse on CAR_B

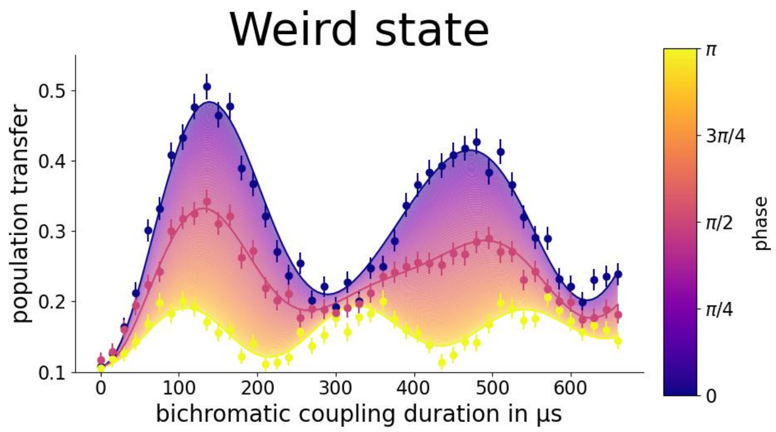
$$\frac{1}{8}\left\{|\downarrow,0,0\rangle+|\uparrow',0,0\rangle+e^{i\varphi_1}|\downarrow,1,1\rangle+e^{i\varphi_1}|\uparrow',1,1\rangle\right.$$
$$\left.+e^{i\varphi_2}|\uparrow',0,1\rangle+e^{i\varphi_2}|\downarrow',0,1\rangle+|\uparrow',1,0\rangle+|\downarrow',1,0\rangle\right\}$$

Here we discard 50% of the population with a second round of postselection and obtain the final state as:

$$\frac{1}{4}\left\{|\uparrow',0,0\rangle+|\uparrow',1,0\rangle+e^{i\varphi_2}|\uparrow',0,1\rangle+e^{i\varphi_1}|\uparrow',1,1\rangle\right\}$$

$\downarrow$ π pulse on CAR_B

$$\frac{1}{4}|\downarrow\rangle\left\{|0,0\rangle+|1,0\rangle+e^{i\varphi_2}|0,1\rangle+e^{i\varphi_1}|1,1\rangle\right\}$$



The product state

$$|\Upsilon_{\boldsymbol{\pi}}\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle - |1\rangle)$$

- Decomposition in bright and dark states

$$|\Upsilon_{\pi}\rangle = \frac{1}{2}\left(|\psi_-^0\rangle - \sqrt{2}|\psi_-^1\rangle + \frac{1}{\sqrt{2}}\left[|\psi_-^2\rangle - |\psi_+^2\rangle\right]\right)$$

- Only one contribution of a bright state
- Transfer rate:

$$g\sqrt{2N} = 2g$$

- Transfer amplitude:

$$\left(\frac{1}{2}\cdot\frac{1}{\sqrt{2}}\right)^2 = \frac{1}{8}$$

$$|\Upsilon_{\boldsymbol{0}}\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)$$

- Decomposition in bright and dark states

$$|\Upsilon_0\rangle = \frac{1}{2}\left(|\psi_-^0\rangle + \sqrt{2}|\psi_+^1\rangle - \frac{1}{\sqrt{2}}\left[|\psi_-^2\rangle - |\psi_+^2\rangle\right]\right)$$

- Two bright state contributions
- Transfer rate:

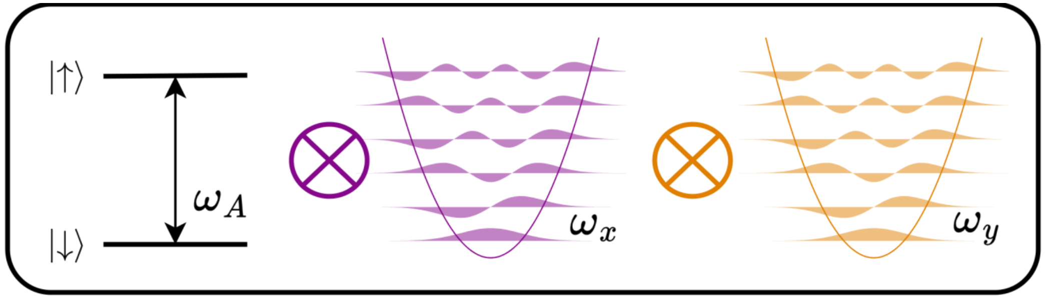
$$g\sqrt{2N} = \sqrt{2}g$$

- Transfer amplitude:

$$\left(\frac{1}{2}\cdot\sqrt{2}\right)^2 = \frac{1}{2}$$

Theory

$$H = g\,(a_x + a_y)\sigma^+ + g\,(a_x^\dagger + a_y^\dagger)\sigma^-$$



Two-mode basis

$$\left|\psi_n^N\right\rangle = \sum_{m=0}^{N} C_n^N \;|m, N-m\rangle$$

$n = 0, N$

Bright and dark states

$$\left|\psi_\pm^N\right\rangle = \sqrt{\frac{N!}{2^N}}\,\sum_{m=0}^{N} \frac{(\pm 1)^m}{\sqrt{m!(N-m)!}} \;|m, N-m\rangle$$

Villas-Boas, C. J. *et al.* Bright and dark states of light: The quantum origin of classical interference *arxiv 2021*